THEODOLITE MEASUREMENTS OF CREEP RATES ON SAN FRANCISCO BAY REGION FAULTS

99 -HQ-GR-0084

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Program Element II

Key words: Neotectonics, Creep Measurements

We continued measuring creep (aseismic slip) rates on San Francisco Bay region active faults. Over the past 21.1 years, we have made over 2500 creep measurements, with about 1700 of these occurring in the eleven years following the Loma Prieta earthquake (LPEQ). Amount of slip is determined by noting changes in angles between sets of measurements taken across a fault at different times. This triangulation method uses a theodolite to measure the angle formed by three fixed points to the nearest tenth of a second of arc. The amount of slip between measurements can be calculated trigonometrically using the change in average angle. The precision of our measurement method is such that we can detect with confidence any movement more than 1-2 mm between successive measurement days.

We presently have regular measurement sites at 27 localities on active faults, plus data from six sites that had to be abandoned. Locations of the San Francisco Bay region sites are shown on Figure 1. We also have one measurement site on the San Andreas fault in the Point Arena area and two on the Maacama fault in Willits and Ukiah that do not appear on Figure 1. We typically remeasure most sites with a history of creep about once every two to three months and most sites without any creep history about every three to four months. In addition to our ten regular sites on the Hayward fault, we have established 24 additional sites in conjunction with J. Lienkaemper of the USGS. We began measuring each of these additional sites annually in July - August 1994.

All measurement sites span a fault width of 57-267 m, except Sites 8 and 20 that span a greater width because of site considerations. This fault width spanned (W) is noted onFigures 2 through 7 and represents the distance from the theodolite on one side of a fault to a target on the other side of the fault. Most of the figures show the time of the 17 October 1989 LPEQ as a vertical line and one (Figure 5) also shows the time of the 24 April 1984 Morgan Hill earthquake (MHEQ) and the 6 August 1979 Coyote Lake earthquake (CLEQ). These figures also show the average rate of movement at each site as determined by the slope of the least-squares line which also appears on each of the graphs. The simple average determined by dividing the total net displacement by the total time measured and the pre-LPEQ rates are also shown, whereas the standard deviations, which in almost all cases are ±0.1 or ±0.2 mm/yr, are not. This report updates our results through 31 October 2000.

SAN ANDREAS FAULT (see Figure 2) - All five of our measurement sites (18, 14, 10, 22, and 23) along the previously locked portion of the fault both northwest and southeast of the LPEQ aftershock zone have remained locked, showing <1 mm/yr of creep. Site 25 near the northwestern end of the central creeping portion of the fault just southeast of San Juan Bautista and the LPEQ aftershock zone had about 5 mm of right slip triggered by the LPEQ (Schulz, 1989). Since the LPEQ, the fault at this site has been moving at about 11 mm/yr, about 4 mm/yr faster than the rate that the USGS had been measuring by creepmeter at this site for about 20 years prior to the quake (Schulz, 1989). This faster rate is consistent with calculations of static stress changes due to the LPEQ by Reasenberg and Simpson (1992). Site 23 at Cannon Road just north of San Juan Bautista was destroyed by a massive landslide after our last measurement on 14 Feb 98.

HAYWARD FAULT (see Figures 3 and 4) - We have been measuring horizontal slip at five sites (1, 2, 12, 13, and 17) along the Hayward fault for about 20-21 years and at five additional sites (24, 27, 28, 29, and 34) since the LPEQ. Along with J. Lienkaemper of the USGS, we have been making annual measurements at 24 additional sites (not shown on Figure 1) since July - August 1994.

We measured an overall right-lateral creep rate of about 4.5-5 mm/yr on most of the Hayward fault in the decade before the LPEQ. Although the creep characteristics (steady or episodic) differed from site to site, the overall rates were quite similar. Detailed analyses of our results appear in previous NEHRP reports and indicate that the LPEQ caused an overall slowdown in the rate of right-lateral creep along the Hayward fault, particularly near the northwestern end of the fault in San Pablo and near the southeastern end in Fremont. The LPEQ apparently caused the pre-quake right-lateral creep rates on the Hayward fault from San Pablo to Fremont to decrease for several years. Overall creep rates along most of this portion of the fault are now back to about 4.5-5 mm/yr, about the same as they were before the LPEQ. The present rate is slower (see Figure 3, Sites 28 and 29), about 3-4 mm/yr, along a 10-15 km-long segment of the fault in Oakland that we had not been measuring prior to the LPEQ.

Creep rates on the southeasternmost portion of the fault in Fremont (Sites 24 and 27), however, showed right slip about 4 mm/yr faster than the rest of the fault for decades prior to the LPEQ (Harsh and Burford, 1982; Lienkaemper and others, 1991). For more than six years following the LPEQ, we measured very little net slip at either of these sites. In fact, both sites showed a slight amount of left slip for about 4-5 years following the quake. In February 1996, however, we measured about 2 cm of right slip at both sites. This is the largest amount of creep over a short period of time ever measured on the Hayward fault (see Figure 4) and suggested a return to faster creep for this portion of the fault. However, this appears not to be the case. Site 24 has been creeping at only about 2.7 mm/yr since the February 1996 event and Site 27 has been creeping at a modest 4.1 mm/yr.

All the post-LPEQ rate changes on the Hayward fault are consistent with Reasenberg and Simpson's (1992) calculations of static stress changes due to the LPEQ (also see Galehouse, 1997; Lienkaemper and Galehouse, 1997; Lienkaemper and others, 1997; and Lienkaemper and Galehouse, 1998).

CALAVERAS FAULT (see Figure 5) - Slip at both sites (4 and 6) on the Calaveras fault in the Hollister area has been episodic with intervals of relatively rapid right slip typically lasting a couple months or less alternating with longer periods of time when little net slip occurs. The LPEQ occurred during an interval of slower movement that had persisted for about a year at both sites. The earthquake apparently triggered up to 14 mm of right slip at Site 4 and up to 12 mm of right slip at Site 6. After the rapid slip triggered by the LPEQ, both sites in the Hollister area returned to a slower mode of movement that persisted for several years. This creep slowdown on the southern Calaveras fault is consistent with the static stress change following the LPEQ proposed by Reasenberg and Simpson (1992). The slowdown was not as pronounced at Site 4 and now the pre- and post-LPEQ rates are virtually the same. At Site 6, the fault had no net slip for nearly four years following the LPEQ but resumed creeping in mid-1993 at a rate a couple of mm/yr slower than before the quake.

A more detailed discussion of the right slip triggered by the Loma Prieta earthquake on the Calaveras fault in the Hollister area is in Galehouse (1990). This paper also discusses the effect of the Morgan Hill earthquake in 1984. No immediate surface displacement had occurred at either of the Hollister area sites when they were measured the day after the Morgan Hill earthquake. However, within the following 2.5 months, both sites showed over a cm of right slip that was followed by a relatively long interval of slower slip (see Figure 5).

In contrast to the sites in the Hollister area, Site 19 in San Ramon near the northwesterly terminus of the Calaveras fault was not affected by either the MHEQ or the LPEQ. It remained virtually locked throughout the first 12 years of our measurements, including three years following the LPEQ. However, the fault at this site has shown net right slip of over three cm at a rate of 3.9 mm/yr for the past eight years (seeFigure 5). This suggests that the northern Calaveras fault became "unlocked" in late 1992 - early 1993 which could have implications regarding its future seismicity.

In January 1997, we began filling in the data gap between Sites 19 and 6 by establishing two new measurement sites on the Calaveras fault. Preliminary data from Site 32 show large variations between measurement days and a rate of about 3.5-4 mm/yr for the past 3.7 years. Site 33, however, is an old USGS site (Coyote Ranch) measured between 1968-1988 which showed creep at 17.2 mm/yr for about 20 years. Our new data (16.3 mm/yr for the past 3.7 years) added to that of the USGS give an average rate of 16.5-18 mm/yr for the past 32.4 years, the fastest creep rate in the greater San Francisco Bay region.

CONCORD - GREEN VALLEY FAULT (see Figure 6) - Typical movement characteristics at Sites 3 and 5 on the Concord fault in the City of Concord are intervals of relatively rapid right slip of about 7-10 mm over a period of a few months alternating with intervals of relatively slower right slip of about 1-2 mm/yr over a period of several years. The latest interval of rapid right slip occurred near the end of 1996. For the past 20 years, the overall average creep rate along the Concord fault in the City of Concord is about 3-3.5 mm/yr. It appears that the LPEQ had no effect on the Concord fault.

Large variations between measurement days tend to occur at Site 20 on the Green Valley fault near Cordelia, possibly because of the seasonal effects of rainfall and/or because logistical considerations resulted in our survey line being particularly long (352.9m). A series of logistical problems prevented us from obtaining any new data from this site between 28 Feb 99 and 12 Mar 00 when we resumed measurements. Regarding a relationship between the Green Valley and Concord faults, episodes of relatively rapid slip and relatively slower slip tend to occur at different times and the rate of slip is about a mm/yr higher on the Green Valley fault (about 4-4.5 mm/yr for the past 16.3 years). The episodic nature of the slip and the duration of the faster and slower intervals, however, are similar. Based on these similarities and the small step between their respective trends, we consider the Concord and Green Valley faults to be different names for the southeastern and northwestern segments of the same fault system.

MAACAMA FAULT (see Figure 7) - The Maacama fault extends from northern Sonoma County to north of Laytonville in Mendocino County and is the northwesterly continuation of the Hayward-Rodgers Creek fault trend (Galehouse and others, 1992). At Site 26 in Willits, the Maacama fault has been creeping right-laterally at about 6.5 mm/yr for the past 8.9 years. Just east of Ukiah at Site 31, the fault shows about 4-5 mm/yr of right slip for the past 7.4 years. These results suggest that the Maacama, along with the Green Valley, are California's fastest creeping faults north of 38° latitude.

SEAL COVE-SAN GREGORIO FAULT - Virtually no creep (less than one mm/yr) has occurred at Site 7 on the Seal Cove fault segment over the past 20.7 years or at Site 8 on the San Gregorio fault segment over the past 18.2 years. Both sites, however, show large variations from one measurement day to another, probably due in part to the large fault widths (266.6 m and 455.0 m) being measured. The LPEQ does not appear to have had any noticeable effect on the rate of movement at either of the sites on this fault system.

RODGERS CREEK FAULT - We measured Site 16 on the Rodgers Creek fault in Santa Rosa from August 1980 until we had to abandon it for logistical reasons in January 1986. During these 5.4 years of measurements, no significant surface slip occurred and we concluded that the Rodgers Creek fault was not creeping at this site.

In September 1986, we established Site 21 on the Rodgers Creek fault near Penngrove (see Figure 1). The average at Site 21 has been about a mm/yr of right-lateral slip for the past 13.9 years. However, there appears to be a lot of surface "noise" at this site and in mid-1993, we discovered that one of our triangulation points had become unstable. We have since reconfigured our measurement array but at present, it is difficult to know whether or not the Rodgers Creek fault is really creeping very slowly or whether the low rate is due to nontectonic reasons. The LPEQ does not appear to have had any effect on the Rodgers Creek fault at Site 21.

WEST NAPA FAULT - There was no net slip on the West Napa fault after 18.5 years of measurements, although there was a lot of surface "noise" at Site 15. The LPEQ does not appear to have had any effect on the West Napa fault. We had to abandon this site for logistical reasons in January 1999.

ANTIOCH "FAULT" - The average rate of movement had been virtually zero for 19.8 years at Site 11 when it was destroyed following the 27 Feb 00 measurement. The rate was about a mm/yr at Site 9 when it had to be abandoned in July 1990. The LPEQ did not appear to have had any noticeable effect at either of these sites on the Antioch "fault".

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Non-technical Project Summary

During 2000 we continued our theodolite measurements at 28 sites that cross faults in the seismically active San Francisco Bay region. Our primary purpose is to determine the rates of present fault movement and to discover any changes in these rates that might occur before, during, or after a seismic event. The central San Andreas, Hayward, Calaveras, Concord, Green Valley, and Maacama faults are all creeping at rates between about one-eighth and three-fourths inches per year. The Seal Cove-San

Gregorio, Rodgers Creek, West Napa, Antioch, and northern San Andreas faults are all either not creeping or creeping at less than one-tenth inch per year.